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"System and method for non-contact measurement of a relative displacement or positioning of two adjacent objects by capacitive means and its application to the control of mirrors"

The present invention relates to a system for non-contact measurement of a relative displacement or positioning of two adjacent objects by capacitive means. It also relates to the non-contact measurement method used in this system and to the application of this system to the control of mirrors, in particular to segmented mirrors.

The principal but non-limitative field of application of the present invention is that of giant telescopes with segmented mirrors in which it is necessary to control the Tip, Tilt and Piston devices of the segmented mirrors with high resolution and the Global Radius of Curvature of the mirror, referred to by the term GROC.

The publication "Segmented Mirror Control System Hardware for CELT" by Terry S. Mast and Jerry E. Nelson published in the proceedings of SPIE 2000 thus discloses a control system for segmented mirrors using capacitive displacement sensors for the three-dimensional control of the mirror segments.

The use of capacitive technology edge sensors arranged on the lateral edges of mirror segments is also known.

Furthermore, there are also non-contact systems for measuring the relative positions of conductive copper tracks on smart cards during machining, which use a calculation of the type (CA-CB)/(CA+CB), where CA and CB represent capacitances constituted by two transmitting electrodes and two receiving electrodes in a situation of relative misalignment.

The purpose of the present invention is to propose a non-contact measurement system using capacitive means which has better performance with respect to measurement precision than current capacitive measurement systems, whilst allowing a reduction in production costs.

This objective is achieved with a system for non-contact measurement of a relative displacement or of a relative position of a first object with respect to a second object, comprising:

- a sensor module comprising a transmitting plate fixed to said first object and a receiving plate connected to said second object, said first transmitting plates and said second receiving plate being arranged substantially facing each other and provided with transmitting and receiving electrodes respectively,
- means of applying high-frequency excitation signals to said transmitting electrodes,
- means of taking high-frequency modulated measurement signals from said receiving electrodes, and
- means of processing said measurement signals thus taken in order to supply signals representing the relative displacement or the relative position of said first object with respect to said second object.

According to the invention, the transmitting and receiving electrodes are arranged to constitute a first capacitance varying as a function of the distance separating the transmitting and receiving plates respectively and a second capacitance varying as a function of the relative misalignment of said plates, and the processing means are designed to perform, on the basis of the measurement signals taken, an analogue calculation (i) of a first signal representing the inverse of said first capacitance and (ii) of a second signal representing the ratio of the second capacitance to said first capacitance.

With the non-contact measurement system according to the invention, it is thus possible to provide simultaneously both information representing the relative separation of two objects, for example segmented mirrors, and information representing the misalignment of these two objects, with very high precision made possible by an analogue calculation performed on capacitive measurement signals.

In order to maintain high performance levels, the analogue computer is preferably produced with one or more modulators.

In an advantageous embodiment, the transmitting electrodes comprise at least a first transmitting electrode (T1) with a first polarity, a second transmitting electrode (TA) with said first polarity and

a transmitting electrode (TB) with a second polarity that is the inverse of said first polarity, the receiving electrodes comprising at least a first receiving electrode (R1) substantially facing said first transmitting electrode (T1) and a second receiving electrode (R(A-B)) substantially facing a part of said second transmitting electrode (TA) and a part of said transmitting electrode (TB) of inverse polarity.

The transmitting electrodes can for example comprise two first transmitting electrodes (T1, T2) with the first polarity exhibiting substantially the same first geometric shape, and the receiving electrodes comprise two first receiving electrodes (R1, R2) exhibiting the first geometric shape and arranged within the receiving plate in order to be respectively facing said first transmitting electrodes when said transmitting and receiving plates are in alignment.

The second transmitting electrode (TA) and the transmitting electrode of inverse polarity (TB) exhibit the same second geometric shape, for example rectangular, and are arranged parallel and in close proximity to each other.

The second receiving electrode (R(A-B)) is preferably arranged within the receiving plate such that the projection of said second receiving electrode on the transmitting plate is included within a perimeter including the contours of the second transmitting electrode (TA) and of the receiving electrode of inverse polarity (TB).

The two first transmitting electrodes (T1, T2) and the second transmitting electrode (TA) can be electrically connected and excited by a same high-frequency modulated excitation signal and the two first receiving electrodes (R1, R2) are electrically connected.

The processing means can advantageously comprise means for performing the analogue calculation:

$$1/(C1+C2)$$

where C1 and C2 are the capacitances respectively constituted by the first transmitting electrodes (T1, T2) and the first receiving electrodes (R1, R2) and means of performing the analogue calculation:

$$CA\text{-}CB/(C1+C2)$$

where C1 and C2 are the capacitances respectively constituted by the first transmitting electrodes (T1, T2) and the first receiving electrodes (R1, R2) and where CA-CB represents the capacitance constituted by, on the one hand, the second transmitting electrode (TA) and the transmitting electrode of inverse polarity (TB) and, on the other hand, the second receiving electrode (R(A-B)).

The differential measurement CA-CB can be carried out either with a bi-electrode transmitter and a mono-electrode receiver or with a mono-electrode transmitter and a bi-electrode receiver.

The capacitances C1 and C2 make it possible to avoid the use of two charge amplifiers which would considerably degrade the thermal drift of the electronics.

The separate measurements of (CA-CB)/(C1+C2) and 1/(C1+C2) thus make it possible to carry out radial and axial measurements.

The processing means preferably comprise a preamplifier stage (20) for pre-amplifying the measurement signals respectively taken from the second receiving electrode (R(A-B)) and from the two first, electrically connected, receiving electrodes (R1, R2), upstream of the analogue calculating means (21).

According to another aspect of the invention, an application of the system for non-contact measurement according to the invention for measuring the relative position between two adjacent mirror segments is proposed. In this application, the transmitting and receiving plates respectively are fixed to facing lateral edges of two adjacent mirrors, in close proximity to the active surfaces of said mirror segments.

According to yet another aspect of the invention, there is proposed a method for non-contact measurement of a relative displacement or of a relative position of a first object with respect to a second object, used in a system according to the invention, comprising:

- an application of high-frequency excitation signals to transmitting electrodes arranged on a transmitting plate fixed to said first object,
- a taking of high-frequency modulated measurement signals from receiving electrodes arranged on a receiving plate fixed to said second

object, at least a part of said electrodes, transmitting and receiving respectively, being substantially facing each other when the transmitting and receiving plates respectively are substantially aligned,

- a processing of said measurement signals thus taken in such a way as to provide signals representing the relative displacement or the relative position of said first object with respect to said second object,

characterized in that this processing comprises an analogue calculation (i) of a first signal representing the inverse of a first capacitance and (ii) of a second signal representing the ratio of a second capacitance to said first capacitance, said first capacitance being constituted by at least one of said transmitting electrodes and at least one of said receiving electrodes in such a way as to vary as a function of the distance separating the transmitting and receiving plates respectively and said second capacitance being constituted by at least one other of said transmitting electrodes and at least one other of said receiving electrodes in such a way as to vary as a function of the relative misalignment of said plates.

Other advantages and features of the invention will appear on examining the detailed description of one embodiment, that is in no way limitative, and the attached drawings in which:

- Figure 1 is a diagrammatic representation of the transmitting and receiving plates respectively used in a measurement system according to the invention;
- Figure 2 illustrates a practical implementation of a measurement system according to the invention;
- Figure 3 illustrates a diagrammatic representation of a first example embodiment of the internal structure of a measurement system according to the invention;
- Figure 4 illustrates a practical example of embodiment of the measurement system shown in Figure 3; and
- Figure 5 illustrates a second example embodiment of a measurement system according to the invention.

There will firstly be described, with reference to Figures 1 and 2, an example embodiment of a sensor module used in a non-contact measurement system according to the invention used for controlling a set of segmented mirrors. This sensor module 1, arranged between two mirror segments M, M'

comprises a transmitting plate T fixed to a lateral edge 10 of the segment M and a receiving plate R fixed to a lateral edge 11 of the segment M', these two plates, transmitting T and receiving R respectively, being substantially facing and parallel with each other.

The transmitting plate T comprises, on a thin flat support 12 made of insulating material, two, first and second, transmitting electrodes T1, T2 of positive polarity, square shaped and electrically connected to a third transmitting electrode TA of positive polarity and of rectangular shape arranged between the first and second transmitting electrodes. The transmitting plate T furthermore comprises a transmitting electrode TB of negative polarity whose shape is identical to that of the third transmitting electrode TA and arranged parallel with the latter.

The receiving plate R comprises, on a thin flat support 14 made of insulating material, two square-shaped, first and second, receiving electrodes R1, R2 and a third receiving electrode R(A-B) of rectangular shape arranged between the two, first and second, receiving electrodes R1, R2. The surface of the supports 12, 14 not occupied by said electrodes is metallized and forms an electrostatic shield for these electrodes.

By way of non-limitative example, the supports 12, 14 can be made of hard material, which makes it possible to obtain the required dimensional stability, and are coated with gold.

The supports can also be made of flexible material, such as polyimide, glued onto the mirror. The gluing, with a thin resin, makes it possible to greatly reduce the coefficient of thermal expansion of the sensor and to improve the dimensional stability of the flexible material supporting the sensor, due to the low coefficient of thermal expansion of the mirror. The flexible material can be produced with conventional flexible printed circuit.

As the two plates, transmitting T and receiving R respectively, are arranged in a parallel manner and separated by a distance, in practice of a few mm up to a few cm, there is therefore obtained a first capacitance C1 constituted by the first transmitting electrode T1 and the first receiving electrode R1, a second capacitance C2 constituted by the second transmitting electrode T2 and the second receiving electrode R2, and a subtractive capacitive device CA-CB

constituted, on the one hand, by the third positive rectangular transmitting electrode TA and the negative transmitting electrode TB and, on the other hand, the third receiving electrode R(A-B).

The sensor module 1 is connected by one or more screened cables 15 to an electronic processing module 10 installed in a rack 100 in the standard 3U format which can contain several electronic processing modules and is arranged within a container 101. The screened cable 15 is connected, on the one hand, to electrical conductors connected to the sensor module 1 by means of a first connector 16 and, on the other hand, to the container 101 by means of a second connector 18 and then to the electronic equipment 10 by means of a third connector 17. The rack 100 also includes a multi-channel acquisition module connected to the different electronic processing modules 10 and to an external interface bus 103.

The arrangement of the sensor module 1 between two mirror segments allows quality measurement since it is very close to the optical surfaces. Furthermore, because of the remote nature of the electronic processing modules, there is no heat dissipation in the vicinity of the mirror segments.

There will now be described, with reference to Figure 3, a first example of embodiment of an electronic processing module 2 connected on the one hand to the sensor module 1 via the screened cable 15 and, on the other hand, to a digital acquisition card 3 provided with a microcontroller 30 and a clock 31.

The electronic processing module 2 comprises a first preamplification stage 20 including a first preamplifier 201 and a second ultra low noise preamplifier 202 receiving as inputs a signal taken from the receiving electrode R(A-B) and a signal taken from the two receiving electrodes R1 and R2 connected in parallel respectively. This first preamplification stage 20 has its output connected to an analogue computer 21 whose two output signals are applied as inputs to two 16-bit analogue-to-digital converters 24, 25 providing digital data routed to the microcontroller 30 via an internal bus 300.

The electronic processing module 2 furthermore comprises a high-stability differential amplifier 22 provided for supplying an excitation signal for the three positive transmitting electrodes T1,T2,TA and an excitation signal to the negative

transmitting electrode TB. This differential amplifier 22 receives a reference signal supplied by a reference oscillator 23 controlled by a clock signal generated by the clock circuit 31, and also provides a modulation reference signal applied as an input to the analogue computer 21 which also receives an offset control signal representing an analogue coefficient ko supplied by a digital-to-analogue converter connected to the digital bus 300. Furthermore, the analogue processing module 2 is electrically powered by an electrical power supply module 4 also provided for powering the digital card 3.

The two excitation signals supplied by the differential amplifier 22 are respectively transmitted to the set of positive transmitting electrodes T1, T2, TA and to the negative transmitting electrode TB via two wired connections, 154 and 153 respectively, included in the screened cable 15, whilst the two reception signals taken from the differential receiving electrode R(A-B) and from the two receiving electrodes RA, RB respectively are applied as inputs to the preamplification stage 20 via two wired connections 151 and 152 respectively.

The first preamplifier 201 is provided for supplying a signal representing the difference CA-CB, whilst the second preamplifier 202 is provided for supplying a signal representing the sum C1 + C2. These two analogue signals are applied as inputs to the analogue computer 21 which is arranged to generate two analogue signals

respectively representing the quantity $k\left[\frac{1}{C1+C2}\right]$ and the quantity $K\left[\frac{CA-CB}{C1+C2} \pm ko\right]$.

Figure 4 illustrates a practical example of embodiment of an electronic processing module 21'. The low-noise preamplifiers 201, 202 are connected according to a conventional structure based on operational amplifiers. The differential amplifier 22 comprises a transformer TR comprising a primary winding 221 connected to the output of an amplifier 220 to which is applied an oscillation reference signal Vosc, a first secondary winding 222 provided for supplying a reference voltage Vref used by the analogue computer 21, and two secondary windings 223, 224 with a common centre point provided for supplying the respective excitation signals for

all of the positive transmitting electrodes T1, T2, TA and for the negative transmitting electrode TB.

The analogue computer 21 comprises a first calculation module 21.1 including a mixer circuit 211 receiving on input the signal supplied by the first preamplification stage 201 and representing the quantity CA-CB, the signal supplied by the second preamplification stage 202 and representing the quantity C1+C2, an offset signal supplied by the digital-to-analogue converter 26 and the output signal Vs1z of this first calculation module, and supplying a signal applied as a negative input of a differential amplifier stage 215 whose positive input is connected to a first switch 213 between the output signal of the mixer 211 and earth, this first switch 213 being controlled by the reference voltage Vref.

A second calculation module 21.2 includes a mixer circuit 212 receiving as input the signal supplied by the second preamplifier 202, the reference voltage Vref, and the output signal Vs1G of this second calculation module, and supplying a signal which is applied as the negative input of a differential amplifier stage 216 whose positive input is connected to a second switch 214 between the output signal of the mixer 212 and earth, this second switch 214 also being controlled by the reference voltage Vref.

The respective outputs of the two differential amplifiers 215, 216 are applied as inputs to two demodulator integrator circuits 217, 218 in order to provide the output signals Vs1z, Vs1G of the analogue computer 21. These two output signals are applied as inputs to a multiplexer 249 whose analogue output is applied as input to an analogue-to-digital converter 250 generating digital data intended to be processed by the microcontroller 30 of the digital card 3 of the non-contact measurement system according to the invention.

It is possible to establish that the output signal Vs1z represents the ratio $\frac{n+.CA-n-.CB}{C1+C2}$ where n- and n+ are the respective number of turns of the secondary windings 223, 224 connected to the negative transmitting electrode TB and to all of the positive transmitting electrodes T1, T2, TA respectively.

A second example of embodiment of a measurement system according to the invention will now be described with reference to Figure 5. The components and elements of the first and second examples of embodiment common to Figures 3 to 5 are indicated by common references.

This measurement system S' comprises a sensor module 1 of the type described above and an electronic processing module 500 which uses conventional bridges controlled by means of modulators at the input of charge amplifiers.

The positive transmitting electrodes T1, T2, TA and the negative transmitting electrode TB are fed with high-frequency excitation signals by the feed module 22' controlled by the output signal of the oscillator circuit 520.

The third receiving electrode R(A-B) is connected via a conductor 151 to the input of a first charge amplifier 501, whilst the first and second receiving electrodes R1, R2 are connected via a conductor 152 to the input of a second charge amplifier 502.

A first modulator 511, connected as a multiplier, receives as input: a first output signal Voz of the processing module 500, an analogue signal ko generated by a digital-to-analogue converter (DAC) 26 controlled by a microcontroller (µC), and an analogue signal Vx produced internally by the processing module 500. This first modulator 511, which is associated with a first modulation coefficient m1, supplies an output modulation signal which is applied via a gain K1 and a first reference capacitor Cref1 as an input to the first charge amplifier 501.

A second modulator 512, connected as a divider, with which is associated a second modulation coefficient m2, receives as input: a reference signal Vref, to which a multiplicative coefficient K is applied, and a second output signal Voy of the processing module 500. This second modulator 512 supplies a modulation output signal Vx which is applied, via a gain K2 and a second reference capacitor Cref2, as an input to the second charge amplifier 502.

The reference outputs +Vref and –Vref of the feed module 22' are used for controlling the first and second modulators 511, 512.

The output signal of the first charge amplifier 501 is applied as input to a first high-frequency amplifier 505 whose output is applied as input to a first synchronous demodulator 515. The output signal of this first synchronous demodulator is applied as input to an integrator 517 which supplies the first output signal Voz representing a displacement along the z axis.

The output signal of the second charge amplifier 502 is applied as input to a second high-frequency amplifier 504 whose output is applied as input to a second synchronous demodulator 516 generating a demodulated signal which is applied as input to a second integrator 518 supplying the second output signal Voy.

The two, first and second, synchronous demodulators 515, 516 are controlled by the oscillator circuit 520.

The use of a real zero method measurement for the electronic processing module 500 procures a decisive advantage in terms of resolution performance. This is made possible by the use of a divider modulator and a multiplier modulator and by the fact that the voltage signal Vx is injected into the multiplier module 511.

The output signals Voz and Voy can be expressed as follows:

$$Voz = \frac{1}{m_2}\left[\frac{n^+Ca - n^-Cb}{n^+(C_1 + C_2) - C_1.K_1} * \frac{K_2.Cref_2}{K_1.Cref_1}\right] \pm k0$$

$$Voy = \frac{K.K_2Cref_2.m_2}{n^+(C_1 + C_2) - C_1K_1}$$

In the practical example of embodiment of a measurement system according to the invention, the sensor module inserted between the mirror segments has the following dimensional and electrical characteristics:

Transmitting plate:

Area of the electrodes TA and TB:	20 x 40 mm²
Area of the electrodes T1 and T2:	40 x 40 mm²
Area of the transmitting plate:	50 x 130 mm²

Receiving plate:

Area of the electrode R(A-B):	20 x 30 mm²
Area of the electrodes R1 and R2:	20 x 20 mm²
Area of the receiving plate:	50 x 130 mm²

Inter-plate distance: between 6 and 18 mm

Capacitance (for an inter-plate distance of 17 mm):

CA = CB = 0.15 pF

C1 = C2 = 0.20 pF

Sensitivity along z axis: 30 pF/m

Sensitivity along Y axis: 11 pF/m

In a practical example of embodiment of an electronic equipment associated with the sensor module described above:

Electronic measurement noise on Z axis:	10 nm/Hz$^{1/2}$
Electronic measurement noise on Y axis:	20 nm/Hz$^{1/2}$
Z axis range:	+/- 0.5 mm
Y axis range:	6-18 mm
Offset adjustment:	+/- 0.5 mm
Z axis output signal:	+/- 10 V
Y axis output signal	0-10 V
Output resolution:	15 nm
(analogue-to digital conversion in 16 bits on Z axis)	
Pass band	0-10 Hz
Gain and offset drift:	< 10 nm/°C
Offset control resolution:	15 nm
(analogue-to digital conversion in 16 bits on Z axis)	
Serial interface	
Electrical power supply:	120 or 230 V
8-channel 3U 19-inch format rack	
Length of sensor-electronics cable:	15 m

The invention is not of course limited to the examples that have just been described and numerous modifications can be applied to these examples

without departing from the scope of the invention. The measurement system according to the invention can, in particular, be used for controlling segmented primary mirrors and for adaptive optics and also for controlling secondary mirrors.